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# NAVAL POSTGRADUATE SCHOOL

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# THESIS

**FLOWFIELD COMPUTATIONS OVER THE SPACE SHUTTLE ORBITER WITH A PROPOSED CANARD AT A MACH NUMBER OF 5.8 AND 50 DEGREES ANGLE OF ATTACK**

by

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June 1993

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# Flowfield Computations over the Space Shuttle Orbiter with a Proposed Canard at a Mach Number of 5.8 and 50 degrees Angle of Attack

by

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## ABSTRACT

Advances in computational fluid dynamics (CFD) capabilities in the last decade have allowed engineers to better analyze cases of hypersonic flight. The Space Shuttle Orbiter has increased over 30,000 pounds in weight since its initial design in 1974, resulting in limitations on its operational capability. One of these limitations is the allowable forward center-of-gravity location resulting from lateral-directional and longitudinal controllability constraints. One method to relax this limitation is to employ the use of a canard. A canard can produce an additional nose-up pitching moment to relax the center-of-gravity constraint as well as to alleviate the need for large, lift-destroying elevon deflections required to maintain the high angles of attack required for effective hypersonic flight.

A configuration is developed using known Orbiter aerodynamic data and a canard computational grid is generated. The Orbiter-Canard configuration is analyzed at a Mach number of 5.8 and angle of attack of 50 degrees using the flowfields generated by the OVERFLOW three-dimensional computer code. Comparison is made with a baseline solution and results are presented.

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## ACKNOWLEDGEMENTS

I would like to acknowledge Rob Meyerson of the Aerosciences Branch and Howard Law of the Guidance and Control Systems Branch at Johnson Space Center for the suggestion to pursue this study. I would also like to thank Gordon Kaefer at Honeywell for his assistance in helping me appreciate the problem. Finally, I am grateful to William Chan and Ing-Tsau Chiu of the Applied Computational Fluids Branch at NASA Ames Research Center who allowed me to seek them out for their breadth of knowledge in the "arts" of grid generation, hole boundary definition and the use of OVERFLOW. Computer time for running the OVERFLOW and PEGASUS codes was supplied by the Numerical Aerodynamic Simulation (NAS) Facility at NASA Ames Research Center, Moffett Field, California.

# I. INTRODUCTION

Ever since the Space Shuttle became a reality, improvements to the design have been pursued with zeal. The basic orbiter weight has increased from approximately 153,000 pounds during the initial phase of design to nearly 190,000 pounds today [Ref. 1]. This increase, along with other factors inherent to the complex design, has created a number of new problems for both engineer and pilot. These include the following:

- Landing speeds have increased due to weight growth.
- The elevons are sized for low dynamic pressures. When maneuvering at low speeds with such large control surfaces that significantly change wing camber, large initial forces opposite to those commanded by the pilot can be encountered.
- When maneuvering at high angles of attack during the hypersonic portion of re-entry, required elevon deflections can be high (25 degrees). This deflection can severely limit the allowable outboard elevon control power for roll control. Control can be especially difficult during the Glide-Return-to-Landing-Site (GRTLS) phase of flight.
- Currently the Reaction Control System (RCS) is employed well into the aerodynamic phase of flight limiting the amount of allowable on-orbit use of the system.

All of these, in one way or another, limit the capability of the Orbiter. A properly designed canard control surface may provide a relief to these problems.

The objective of this study is to design an effective control canard to provide enhanced controllability throughout the flight regime. This design will be done by sizing according to existing empirical methods for prediction of forces and existing Orbiter aerodynamic derivatives for various Mach numbers. Consideration will be given to structural integrity, adaptability and heat transfer, though analyses will not be included.

A geometry will be formulated based on the moment required at the extreme flight condition corresponding to the Alpha Hold Phase of the GRTLS abort profile with a forward center of gravity. This maneuver requires the Orbiter to fly at 50 degrees angle of attack at a Mach number of 5.8.

A three-dimensional, Navier-Stokes computational solution for such a configuration will be pursued. The Operational Aerodynamic Data Book (OADB) will be consulted to formulate a baseline to validate the no-canard configuration [Ref. 2]. Results will then be generated for the Orbiter-Canard system at the aforementioned flight condition.

# II. BACKGROUND

## A. EARLIER CANARD STUDIES

Canards have been considered for use on hypersonic vehicles as early as 1966, when research conducted by Brooks and Cone of NASA Langley Research Center studied their feasibility in improving stability [Ref. 3]. Tests were conducted in the Langley 15-inch Hypersonic Wind Tunnel using several wing-body-canard configurations. The effects of vertical wing placement, canard shape, and body length on longitudinal and lateral-directional stability were presented for angles of attack up to 20 degrees at a Mach number of 10.03. Results concluded that for low-wing configurations, the effect of canards was to increase dihedral effect significantly at angles of attack above 12 degrees and to slightly increase directional stability.

In 1984, a study was conducted by the Aerospace Engineering Department at Texas A&M University on the design of a low-speed deployable canard to be used for approach and landing only [Ref. 1]. Two 40-hour wind tunnel tests were conducted in a 7′ X 11′ low-speed wind tunnel with a 0.0405 scale model of the current Orbiter employing some suitable devices. Canards at two longitudinal stations, $X_0$=158.1" and $X_0$=363.5" (measured from the nose of the Orbiter), were tested at flight conditions throughout the landing phase. Baseline data for the Orbiter alone were compared against those obtained from the OADB [Ref. 2]. A forward body flap, designed to deploy from just aft of the nose wheel well, was also tested. A drag chute for landing distance management was also evaluated and is now employed on Endeavor and will be retro-fitted to current Orbiters. Although there were slight discrepancies in the comparison with the baseline, the data taken employing the canard in the landing phase clearly showed an advantage. The canard mounted aft was the most feasible from structural considerations.

The report suggested that the elevons could be deflected down as much as 10 degrees while employing the canard with the Orbiter remaining trimmed with enough pitch control authority for pilot corrections and landing flare. The increase in vehicle lift coefficient from this elevon deflection would decrease the current landing speeds and distances up to 15 knots and 15 percent respectively.

In 1985, more low-speed tests were conducted at NASA Langley by Phillips [Ref. 4]. Several configurations were tested including strake-deployed leading edge extensions and top, bottom and mid-mounted canards. Several sizes were tested at each location. The main objective of this test was to determine the effect of the canards on both the longitudinal and lateral-directional stability of the Orbiter at low speeds and moderate angles of attack.

This study concluded that side-mounted canards gave the best payoff in minimizing canard surface area required, hence added weight, while still achieving the goal of trimming out the nose-down pitching moment created with down-elevon deflection.

This configuration also clearly minimized any negative lateral-directional stability contribution. Its effect was found to be minimal while increasing the dihedral effect slightly for angles of attack below 12 degrees, where the low-speed portion of the re-entry profile is flown.

The studies previously conducted clearly show that the addition of a canard can have a positive effect on performance in the high- and low-speed environments.

## B. COMPUTATIONAL DEVELOPMENT

The capabilities of computational fluid dynamics have allowed engineers to exercise possibilities that were previously unattainable without the use of expensive wind tunnel testing. This is one such case where CFD can be of assistance to aerodynamic designers. Numerous computer codes have been developed for the analysis of flows over aircraft configurations.

The OVERFLOW computer code was developed by Buning et al. at NASA Ames Research Center to calculate the flowfield around complex geometries [Ref. 5]. The code is the most recent upgrade of the popular F3D code that was used for most of the earlier Orbiter and Launch Vehicle flowfield computations and for flows over other complex geometries [Ref. 6]. It incorporates both the F3D algorithm and the ARC3D algorithm described by Pulliam in Ref. 7. Its capability to apply the Chimera scheme to calculate the flow in the presence of multiple grids that overlap makes it especially useful for this geometry [Ref. 8]. This code was run on the CRAY Y-MP at the Numerical Aerodynamic Simulation Facility (NAS) at NASA Ames Research Center.

The PEGASUS code, originally developed at the Air Force Arnold Engineering Development Center, is a preprocessor to the OVERFLOW code [Ref. 9 and Ref. 10]. PEGASUS produces the outer and hole boundary points and provides the interpolation stencils required to run the OVERFLOW flow solver.

Grid generation is arguably the most time consuming part of flow simulation. For this complex geometry, several grid generation tools have been employed. The GRIDGEN2D software package was produced by Steinbrenner and Chawner to generate the outer surfaces of what would eventually become a three-dimensional grid [Ref. 11]. For this project, the versatilities of the GRIDGEN2D program were exploited to generate the body surface grids of the canard glove and canard extension.

Generation of three-dimensional grids using hyperbolic, space-marching partial differential equations is accomplished more easily when compared to their elliptic counterparts where the outer boundary of the volume grid is important [Ref. 12]. The HYPGEN grid generation program, along with the User Interface (UI), were used to generate the three-dimensional grids around the Orbiter, Canard Glove/Extension, and Collar grids [Ref. 13 and Ref. 14].

In order to effectively communicate the finite differenced, Navier-Stokes equations between surfaces such as a wing-body junction, collar grids must be used [Ref. 15]. Collar grids allow the smooth transition from one grid to the next by providing a nearly continuous grid spacing in the areas of surface-to-surface intersection. This smooth transition provides better resolution of the flow field and makes for higher quality interpolation. The methods developed by the Multiple Body Aerodynamics Group at NASA Ames were employed to generate collar grids for the proposed geometry.

Extensive use of the PLOT3D software package developed by Buning et al. was made to process the output from OVERFLOW and to provide a better understanding of the nature of the flowfield [Ref. 16].

# III. METHODOLOGY

## A. PROBLEM SPECIFICS

At present, the forward center of gravity of the Orbiter is limited to 65 percent of the Mean Aerodynamic Chord (MAC). This position restricts the Orbiter's payload carrying capability. The reasons for this restriction are both structural and aerodynamic. The nose wheel must not be allowed to impact on landing such that structural damage would result. The integrity of the vehicle's stability throughout the flight envelope must also be maintained. A canard could provide additional pitch authority to allow the Orbiter to fly with less center-of-gravity-restricted payloads and avoid the associated "nose wheel slapdown" on landing rollout. The canard would also provide nose-up pitching authority by commanding the nose up instead of destroying a significant amount of lift in order to move the tail down. With a canard, the authority necessary to flare the craft without these destructive forces could conceivably be provided, relaxing the pilot workload on what is currently a "squirrelly" landing for even the most skilled of pilots.

In the hypersonic phase of re-entry, the center-of-gravity constraints exist for mainly aerodynamic reasons. The elevons must carry the burden of trimming the vehicle to the high angles of attack required to fly effectively at such conditions. The outboard elevons are used as ailerons for roll control in a region of the re-entry profile that requires many roll maneuvers. The total allowable deflection (trailing edge up) of the elevon is 35 degrees and the maximum aileron deflection is 15 degrees. This deflection limitation means that any elevon deflection for pitch control over 20 degrees limits aileron control; hence, lateral-directional control is degraded. During the GRTLS phase of flight, the most demanding for the Orbiter in a stability-and-control sense, the elevon deflections can be as high as 26 degrees. This high deflection limits the aileron authority to 8 degrees and thereby puts the lateral-directional control criteria to the test. According to the OADB, for M=6.0 and $\alpha$=50 degrees, the rolling moment coefficient due to aileron, is increased from 0.00061 to 0.00086 or 38 percent when the elevon deflection is changed from 26 to 20 degrees. The use of a canard during this phase of flight would relax the need for such high elevon deflections. This lower deflection requirement would restore controllability, allow the forward center of gravity constraint to be relaxed, or provide a combination of both.

There are several potential problems associated with attempting to employ a canard on the current configuration. The added weight, forward of the center of gravity, tends to be self-defeating unless the canard has low weight and performs efficiently to provide the maximum pitching moment for minimum weight. The structural difficulties associated with adding such a surface cannot be overemphasized. The structural loads under dynamic pressures on the order of 375 lb/ft$^2$ are demanding. The canard would need to deploy in such a way as to keep it inside the bow shock of the Orbiter to avoid unbearable heat loads during re-entry. The integrity of the current vehicle is not easily adaptable to such a concept. Changes in the current control laws would need to be accomplished as well, to include the use of the new control surface. The study of control law integration, heat transfer and structural adaptation have not been overlooked here but merely deferred with consideration given to their importance.

## B. REQUIREMENTS/SIZING

The requirements that drive the design of a canard on the current Orbiter are mainly pitching-moment oriented. The canard must provide a certain pitching moment during certain phases of flight if it is going to be useful. Two particular flight conditions were taken in this study to be the most important in so far as pitching moment requirements are concerned. These conditions are the GRTLS case (M=5.8, $\alpha$=50 degrees, Alt=135,000 ft, q=119 psf) and the pre-landing condition (M=0.3, $\alpha$=12 degrees, Alt=2000 ft, q=122 psf).

### 1. GRTLS Case

The requirement used for the GRTLS condition was to relax the required elevon deflection from 26 to 20 degrees.

The required restoring nose-up pitching moment is equivalent to that created by the decrease in elevon deflection as well as the increase in nose-down moment associated with the added weight of the canard forward of the center of gravity. The required pitching moment is given by:

$$M_{c_{req}} = C_{M_{\delta_{el}}} \overline{q} \, S_w \, \overline{c} \, \Delta(\delta_{el}) + W_c \, l_c \tag{1}$$

where $C_{m\delta e}$ is the elevon control power coefficient, q is the dynamic pressure, $S_w$ is the Orbiter wing reference area, c is the Orbiter reference chord, $\Delta(\delta_{el})$ is the change in elevon deflection, $W_c$ is the canard weight and $l_c$ is the canard moment arm about the vehicle center of gravity. This relationship, coupled with aerodynamic performance estimates, was used to size the canard. The derivatives required to calculate the required forces were obtained from the Honeywell Guidance Navigation and Control Branch using the Lateral Variation 09 (LVAR09) Uncertainty Set [Ref. 17]. The LVAR09 set was provided as a worst-case prediction of the current Orbiter derivatives. It should be stressed that these data are not an estimation, but the extreme of an uncertainty band around the data base of measured derivatives provided in the OADB. Using these parameters, a moment of 104,600 ft-lb was calculated.

Originally, DATCOM was consulted to provide the "best guess" of the aerodynamic performance of the canard in the GRTLS case with the realization that the method is considered inaccurate above M=5.0. After further research, Newtonian

Impact theory appeared to be the more correct approach because of its ability to account for local surface slope compared to the "flat plate" assumption used in DATCOM. Using this theory, a reduction in the initial surface area estimate of about 30% could have been realized. However, the flow at this extreme angle of attack is highly separated on the top of the Orbiter and canard, making forces difficult to predict by any method; therefore, the most pessimistic force predictions were used. Initially, in order to reduce separation effects, it was decided that a canard angle of attack of 25 degrees with the highest possible sweep would be used when sizing for the GRTLS condition. Using this angle of attack and DATCOM methods for normal and axial force coefficient estimation, the required canard area was calculated to be $115ft^2$. In addition to the area requirement, the span of the canard must be such that it is fully contained within the bow shock of the Orbiter at this flight condition to avoid unbearable heat loads. The stand-off distance of the shock at the proposed longitudinal station for the placement of the canard had to be estimated. The only reasonable longitudinal location for a canard on the current Orbiter in a structural sense is at $X_o$=582". This is the location of a major bulkhead between the crew compartment and payload bay and corresponds to a canard moment arm ($l_c$) of 41.25 feet for the forward center-of-gravity case. This geometry is shown in Figure 1.

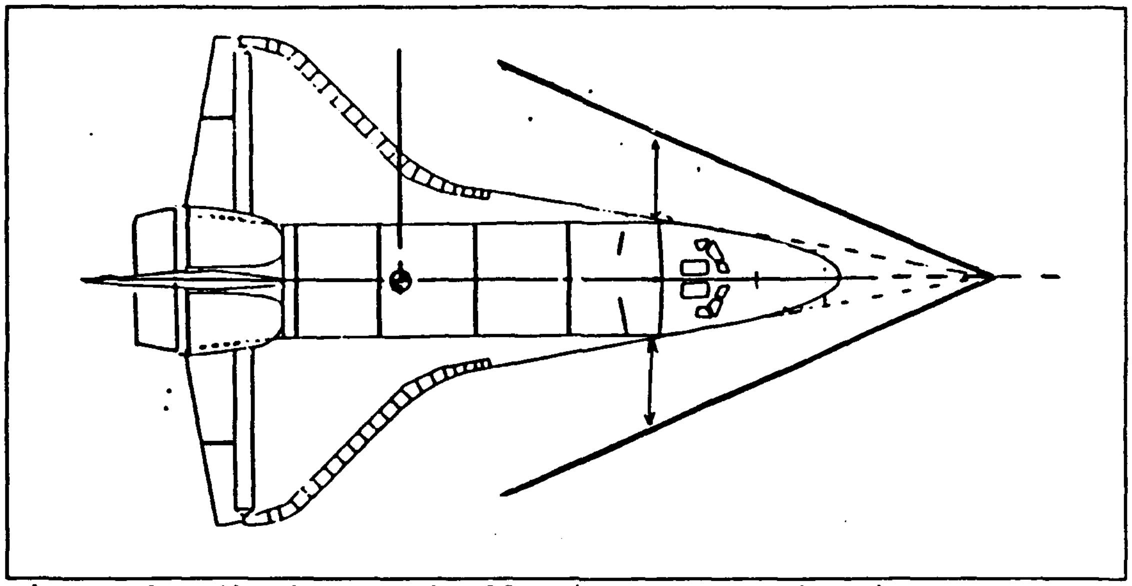

**Figure 1**. Shock Stand-off Distance Estimation Based on Canard Longitudinal Location.

An estimation of the shock stand-off distance was made using tangent-wedge methods suggested by Anderson [Ref. 18] with the understanding that, again, the high angle of attack makes this empirical analysis even more suspect. Using this method for a wedge half angle of 12 degrees, a shock stand off distance of 20 ft was estimated. As a safety factor, the allowable span of the canard for the GRTLS fight condition was set at 12 feet. The challenge then became how to get the required canard surface area inside the proposed bow shock.

**2. Pre-Landing Case**

For the pre-landing case, the requirements for the canard were:

- Trim out the nose-down pitching moment associated with a 10 degree drooping of the elevons.
- Trim out the added weight of the canard forward of the center of gravity.
- Provide an additional 0.15 rad/sec$^2$ pitch rate authority to provide improved pilot handling qualities.

For initial sizing calculations, a desired $C_L$ of 1.6 was used. This value for $C_L$ was chosen as a medium and was thought to be an achievable value for a geometry of this nature. Existing moment derivatives ($C_{m\delta e}$=-0.0088204/deg) were used to calculate the pitching moment requirement associated with drooping the elevons 10 degrees as provided by Gordon Kaefer at Honeywell [Ref. 17]. The governing equation for sizing the canard based on these conditions is given by:

$$C_{L_c} \overline{q} S_c l_c = W_c l_c + C_{m_{\delta_{el}}} \overline{q} S_w \overline{c} \Delta ( \delta_{el} ) + I_{yy} \theta_{req} \quad \textbf{(2)}$$

For the Pre-Landing case, q=122 lb/ft$^2$, $C_{Lc}$=1.6, $W_c$=3000 lbs, $l_c$=41.25 ft, $S_w$=2690 ft$^2$, c=39.6 ft, $I_{yy}$=658,370 ft-lb/sec$^2$, and $\theta_{req}$=0.15 rad/sec$^2$. $\Delta\delta_{el}$=10 degrees. This equation was used to calculate required canard surface areas for given lift coefficients. For a $C_L$ of 1.6, a canard surface area of 175 ft$^2$ would be required. This surface area was thought too high to both fit inside the bow shock of the Orbiter and limit the footprint on the current configuration. At this point, some adjustments were made in the requirement for down-elevon deflection for landing. Reducing the requirement from 10 degrees to 8 degrees would save 58 ft$^2$ of required surface area while increasing the touchdown speed of a 200,000 lb Orbiter from 163 to 167 knots compared to 180 knots for the current Orbiter. This elevon deflection criterion was used for the remainder of the study.

## C. CONFIGURATION DEVELOPMENT

### 1. Configuration Iterations

Several configurations were considered to meet the requirements set forth in the previous section. These options ranged from a constant-geometry, external canard to a fully-retractable device to be deployed only when required and to be stowed fully inside the Orbiter when not in use. The constant-geometry configuration was not feasible because it could not reside entirely within the bow shock in the hypersonic phase of flight nor provide the forces necessary in the Pre-landing phase of flight. After consulting with Rob Meyerson at NASA Johnson Space Center, the fully-retractable design was not considered because it would seriously impact the surface integrity and require too much re-engineering on the current Orbiter [Ref. 19]. A combination of the two was finally employed as the final configuration. An all-moving glove (in pitch) consisting of a symmetric airfoil would be used to house a more efficient high-lift airfoil to be deployed (i.e., swept out) in the flight regimes that warranted such a geometry. A leading edge sweep of 45 degrees was chosen for the glove to coincide with the Orbiter main wing for launch vehicle considerations. The GRTLS configuration was then chosen based on the surface area requirement coupled with the estimated shock stand-off distance. The final configurations for both cases are shown in Figure 2.

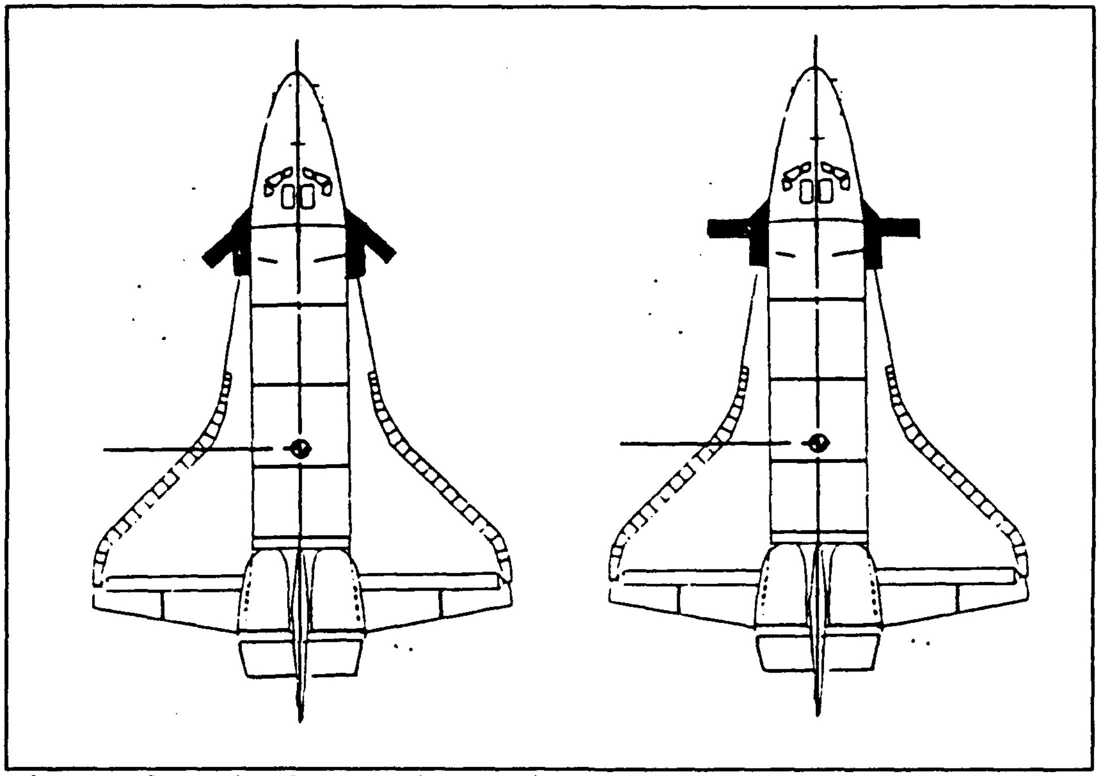

**Figure 2**. Final Configurations for the GRTLS and Pre-Landing Cases.

### 2. Airfoil Selection

As airfoil selection was not the thrust of this study, airfoils for the canard glove and extension were chosen based on existing data without an in-depth study being performed to consider their being optimum for this case. The symmetric NACA 0012 airfoil was chosen for the glove assembly so as to not significantly affect the performance of the Launch Vehicle. The current Orbiter airfoil is a derivative of the NACA 0012 as well. For the extension, the airfoil selected was the Natural-Laminar-Flow (NLF(1)-0215F) airfoil. This airfoil was selected for its performance in conditions where the surface texture is not smooth as would be expected when thermal protection is required. The NLF(1)-0215F airfoil also exhibits a high $C_{l_{max}}$ (~1.7) coupled with a gentle stall break. [Ref. 20]

The total lift coefficient for the canard for the low speed case will be reduced by the effect of low aspect ratio and interference between the two separate airfoil shapes.

## D. CFD MODELING METHODOLOGY

The GRTLS case was chosen to model for the purposes of generating a computational solution. Modeling the configuration consisted of four steps:

- Surface Grid Generation
- Volume Grid Generation
- Collar Grid Generation
- Hole Boundary and Interpolation Stencil Definition

### 1. Surface Grid Generation

The GRIDGEN software package was chosen to generate surface grids because of its ability to allow the manual movement of grid points [Ref. 11]. This feature was invaluable when dealing with sharp wing tips and trailing edges and was also very helpful in the generation of the volume grid which will be discussed later. Once this software was mastered, the generation of the surface grids, though time consuming, was straightforward. The surface grids for the glove and NLF extension were generated on the IRIS4D workstation in the Naval Postgraduate School, Department of Aeronautics and Astronautics Computational Fluid Dynamics Laboratory. Several line and point manipulation routines were written to provide better grids and to convert data formats to a compatible form for use with the volume grid generation software. Routines written by Buning et al. at NASA-AMES, provided for use with the PLOT3D software, were used as well [Ref. 16]. The surface grids for the NLF extension and glove are shown in Figures 3 and 4.

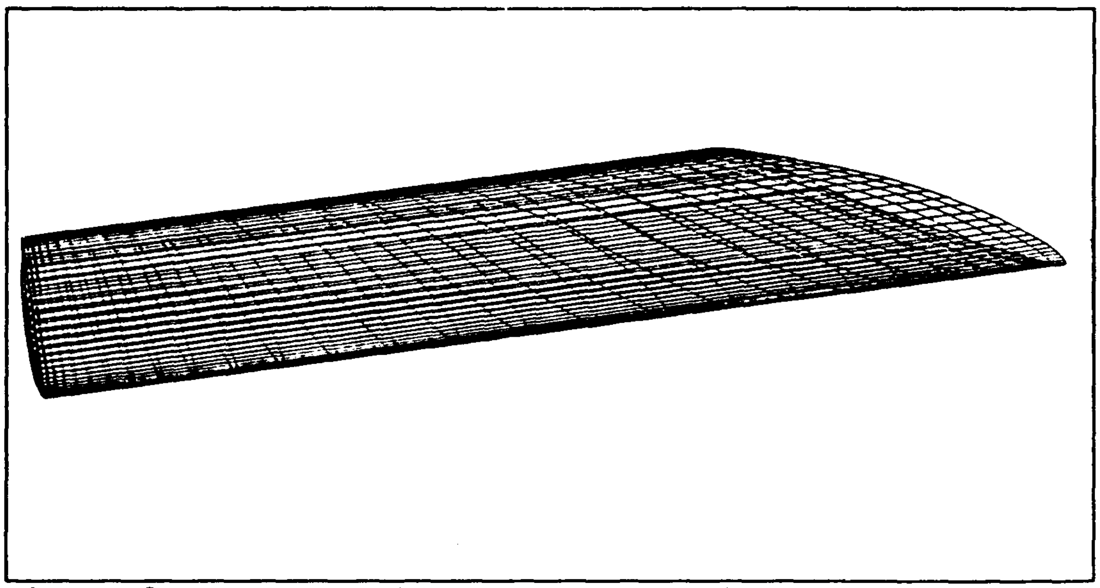

**Figure 3**. Surface Grid for NLF Extension.

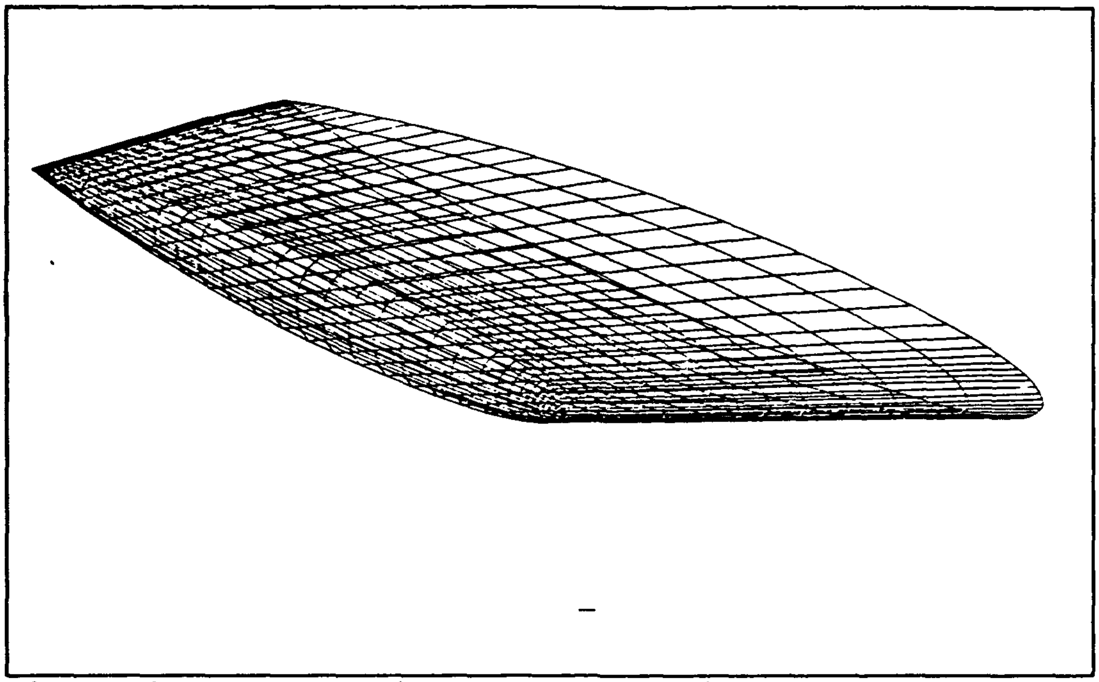

**Figure 4**. Surface Grid for Glove Device.

### 2. Volume Grid Generation

Once a suitable surface grid was generated, the HYPGEN/UI routine was employed to generate the volume grid [Ref. 13 and Ref. 14]. The HYPGEN software uses hyperbolic partial differential equations to generate volume grids according to user specified boundary conditions and smoothing parameters. This software was used with the User Interface (UI) software that allows for easy manipulation of input parameters. This capability is especially important when dealing with complex geometries where the correct input parameters can be elusive. Viscous spacing normal to the surface was calculated based on the method outlined in Ref. 21. The HYPGEN/UI routine provided an initial volume grid that was easily manipulated to provide the desired grid topology. O-grids were generated for all airfoils. The main reason for not employing a C-grid was that the wake of the airfoil, at 50 degrees angle of attack, will be on its upper side and a concentration of points at the trailing-edge would not be computationally efficient. Several post-processing routines were again written to best manipulate the HYPGEN/UI output. The volume grids for the glove and NLF extension are shown in Figures 5 and 6.

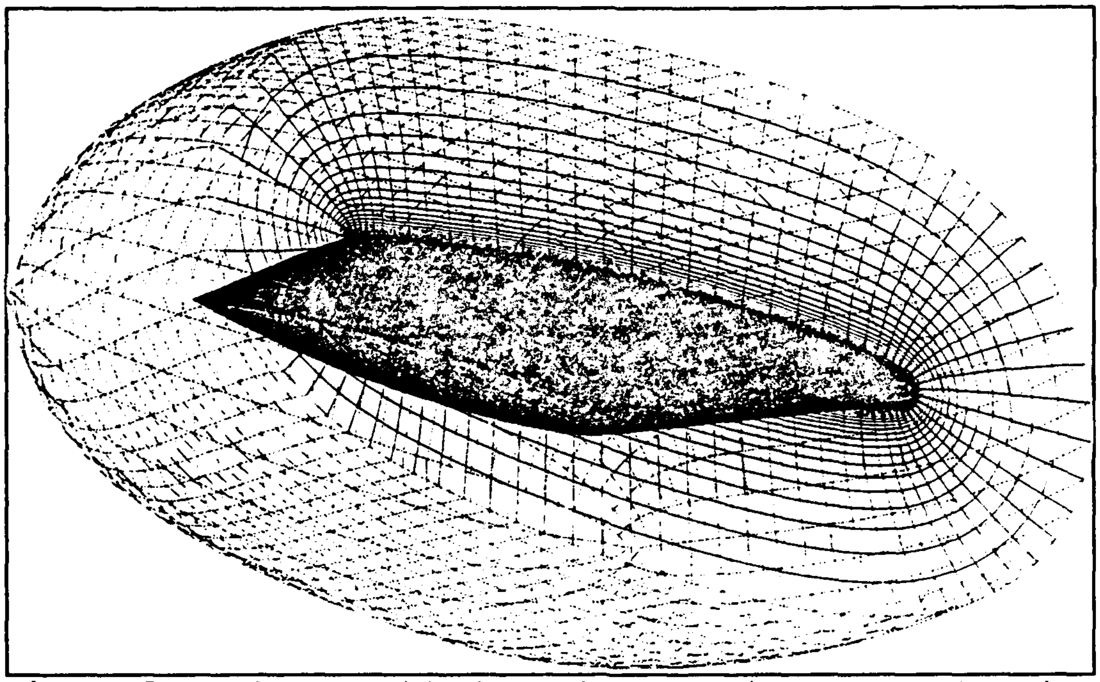

**Figure 5**. Volume Grid for Glove Device created using HYPGEN/UI.

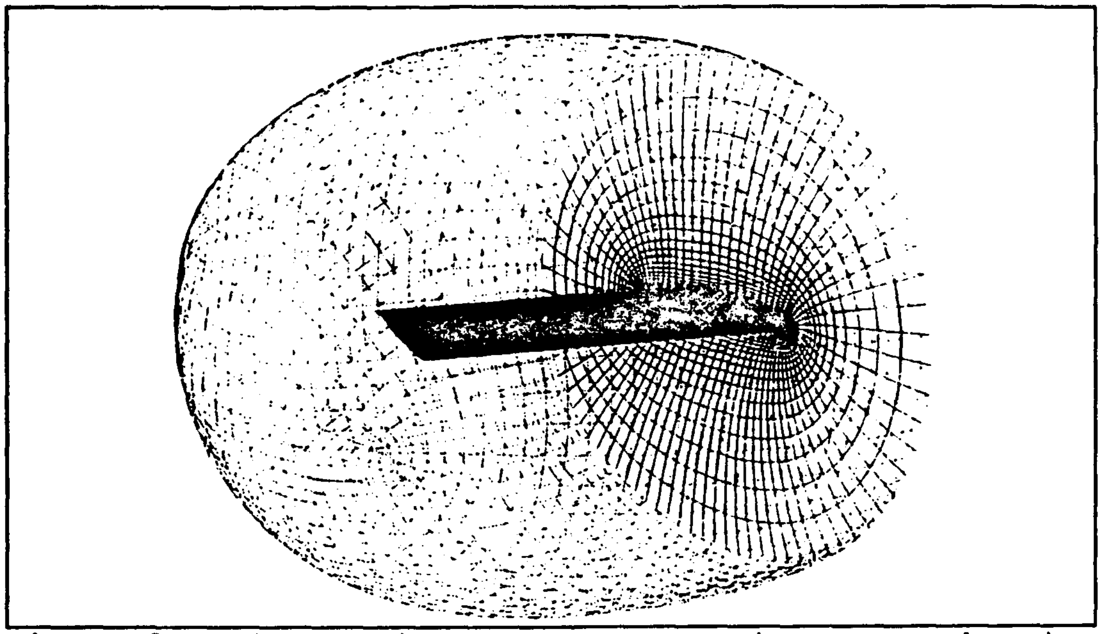

**Figure 6.** Volume Grid for NLF Extension created using HYPGEN/UI.

The surface grid for the Orbiter was obtained from Buning at NASA Ames. After consideration of the computational time and effort required to compute the flow over the entire Orbiter, it was decided to use a forward 73 feet of the half-body instead of the entire 121 feet. This geometry satisfied the requirement of determining the force transmitted from the canard to the Orbiter. Once the forces were obtained, they could be compared with predictions and equated to an allowable elevon deflection relaxation for the GRTLS condition. The volume grid for the Orbiter was generated using HYPGEN/UI. The volume grid for the Orbiter is shown in Figure 7.

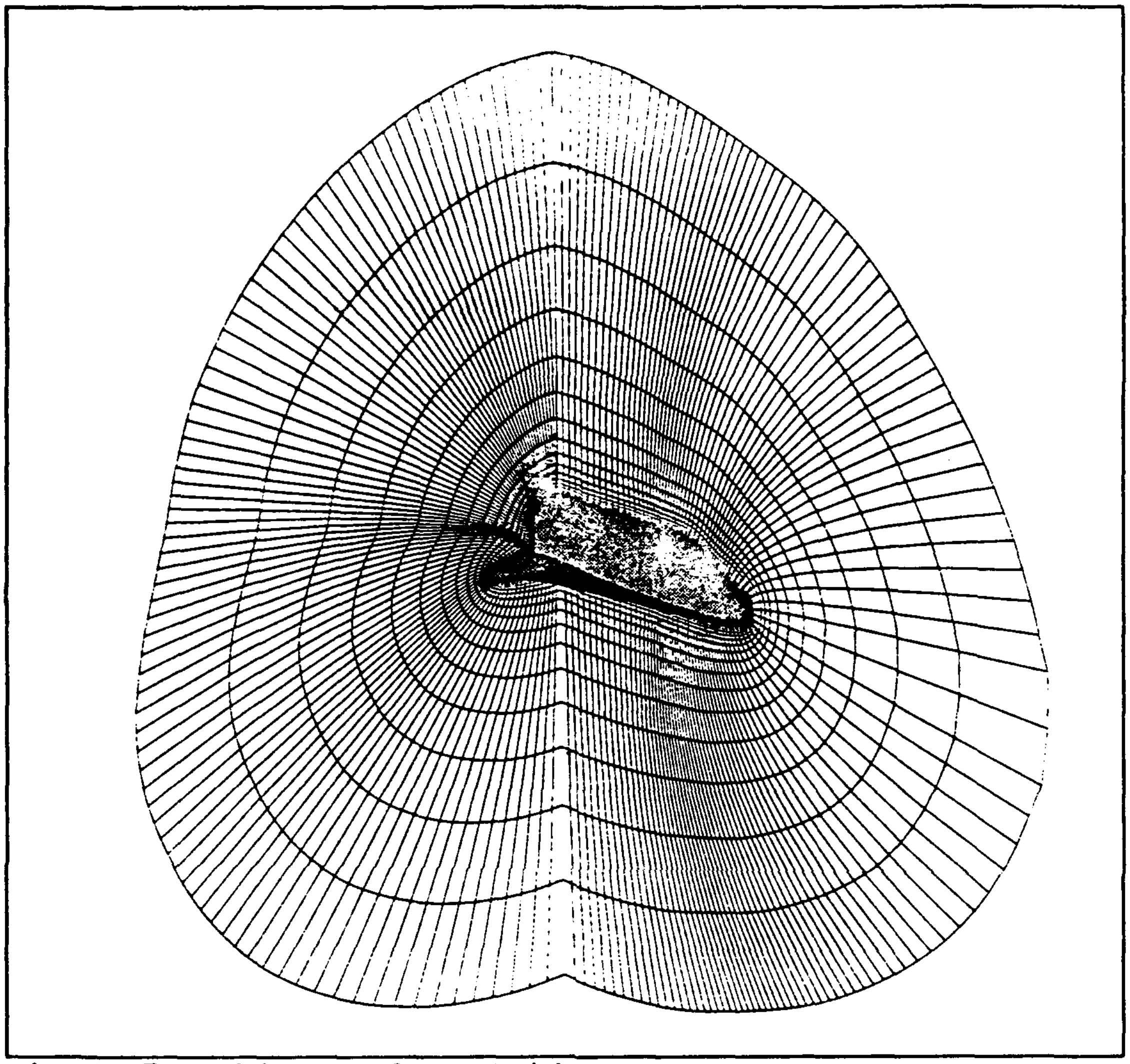

**Figure 7**. Orbiter Volume Grid.

### 3. Collar Grid Generation

Collar grids provide a smooth means of communication between two intersecting geometries. Collar grids were generated for the intersection of the glove and Orbiter and for the joining of the glove and NLF extension. The collar grids were generated in three steps. First, the line of intersection of the two surfaces was determined. This was accomplished with the LSECT4 routine written by Chiu of NASA Ames [Ref. 15]. Second, surface grids were generated that conform to each of the two intersecting surfaces and grow from the previously generated intersection line. This was done with the SURGRD and COLMERGE routines written by Chan and Chiu, respectively, at NASA Ames [Ref. 15]. Lastly, the volume grids for the collar surface grids were generated using HYPGEN/UI. The two collar grids are shown in Figures 8 and 9.

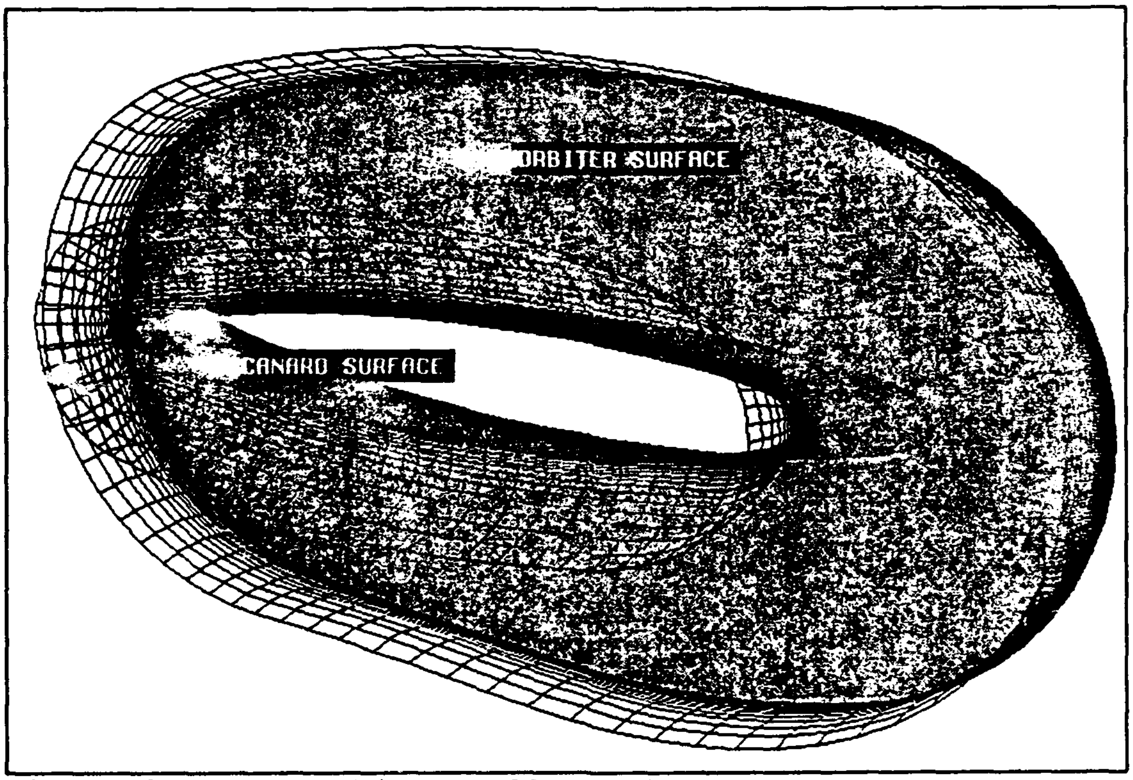


**Figure 8**. Glove-Orbiter Collar Grid

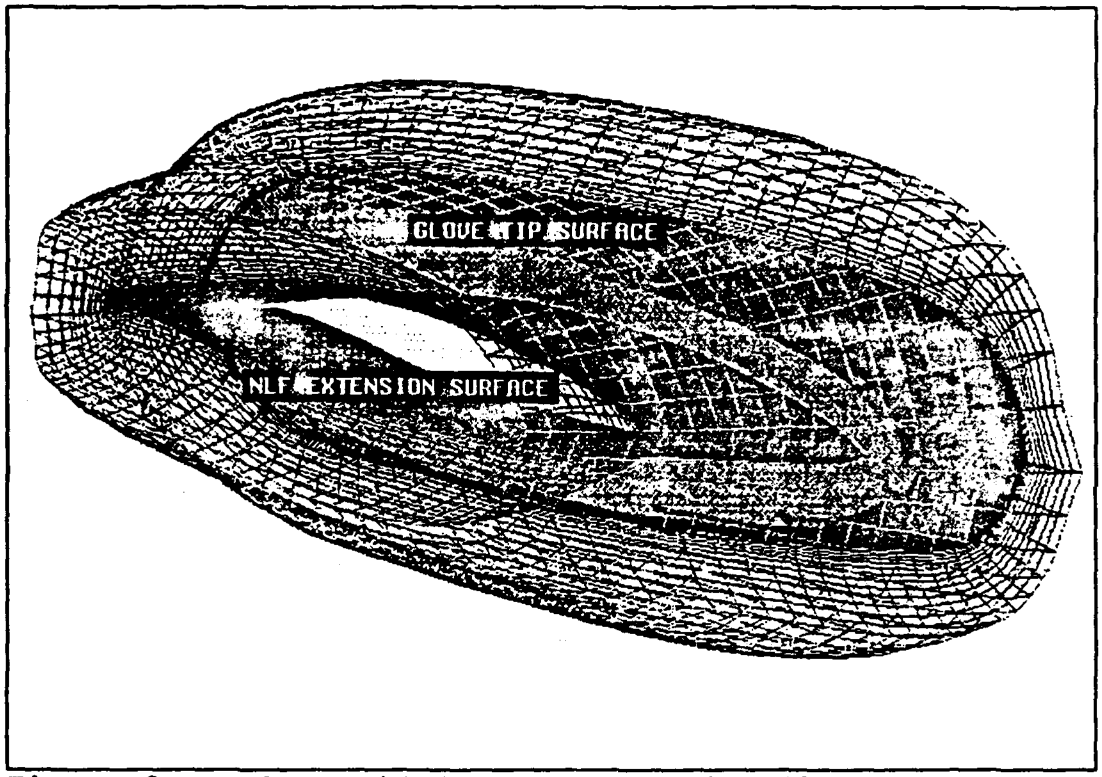

**Figure 9**. Collar Grid for NLF Extension-Glove

**4. Hole Boundary and Interpolation Stencil Definition**

After the collar grids were generated, the points that define the boundary of the overlap of the grids were defined using the PEGASUS code provided by Buning [Ref. 10]. This process consists of defining the holes to be cut in one grid by the other, thereby eliminating or "blanking out" those points in the hole while allowing enough overlap for interpolation. These hole cutters were defined as input to PEGASUS. The PEGASUS code was run on the CRAY Y-MP at NAS. Several iterations were required to blank out only the necessary points in the Orbiter, glove, and NLF extension volume grids that were, in fact, overlapped by other grid points for proper interpolation quality. The output of the PEGASUS routine is both a multiple grid data file containing all of the grids with the proper points blanked out and the interpolation stencils between the overlapping points for input into the OVERFLOW flow solver.

## E. FLOW SOLVER EMPLOYMENT

The OVERFLOW Navier-Stokes code is a rewrite of the F3D/CHIMERA time-marching code developed by Joseph Steger and co-workers at NASA Ames [Ref. 5 and Ref. 8]. The code solves the Reynolds-Averaged Navier-Stokes equations in Strong Conservative form using either the F3D or ARC3D algorithms [Ref. 7 and Ref. 6]. The OVERFLOW code was chosen for its ability to solve flows over complex geometries and versatility in turbulence modeling.

### 1. Baseline Solution Generation

The solution for the baseline Orbiter without a canard was generated for comparison. The baseline case also provided a familiarization with the OVERFLOW code and its input and output data file formats. The Baldwin-Barth one-equation option was used as a turbulence model for both solutions [Ref. 22]. This model was chosen because it provides better turbulence modeling for complex flows. The other option for the OVERFLOW code is to use the Baldwin-Lomax algebraic model [Ref. 23]. The solution was advanced until the computed residuals were decreased by about two orders-of-magnitude or the solution no longer changed considerably for subsequent iterations. The time step and smoothing parameters were adjusted throughout the solution advancement to both accelerate convergence and avoid divergence. The restart capability of the OVERFLOW code was vital to meeting the challenge of convergence for a highly-separated, hypersonic flowfield. The Mach number contours of the solution are shown in Figure 10.

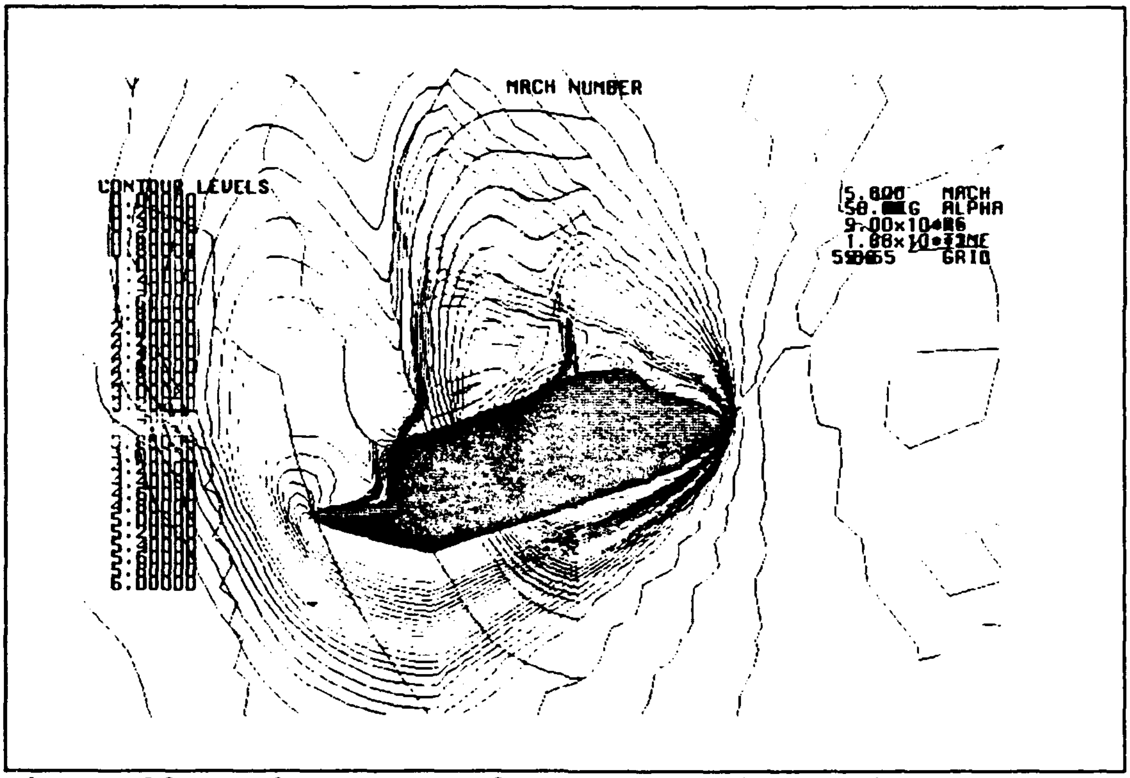


**Figure 10. Mach Contours for the Baseline Orbiter Case.**

## 2. Orbiter-Canard Solution Generation

Once a solution for the baseline was achieved, work was begun on the advancement of the Orbiter-Canard solution. The five grid system was run through PEGASUS as previously mentioned. Two data files were created by PEGASUS for use by the OVERFLOW flow solver. These files contain all of the boundary interpolation stencils for the five grids and the IBLANK information to omit the proper points in grids that are superseded by grid points in overlapping grids respectively.

The increased complexity of the geometry and corresponding flowfield around the Orbiter-Canard system make the advancement of a computational solution much more challenging. The time step required to advance the solution without divergence was around two orders of magnitude less than that allowed for the baseline. This limitation required more iterations to converge the solution. The Orbiter and glove grids showed better convergence and therefore could be run at a higher time step. The collar grids and the NLF extension grid required lower time steps for convergence. Once the solution residuals were monotonically converging, the time step was increased in each of the grids to force a quicker convergence. The Mach number contours of the Orbiter-Canard system are shown in Figure 11.

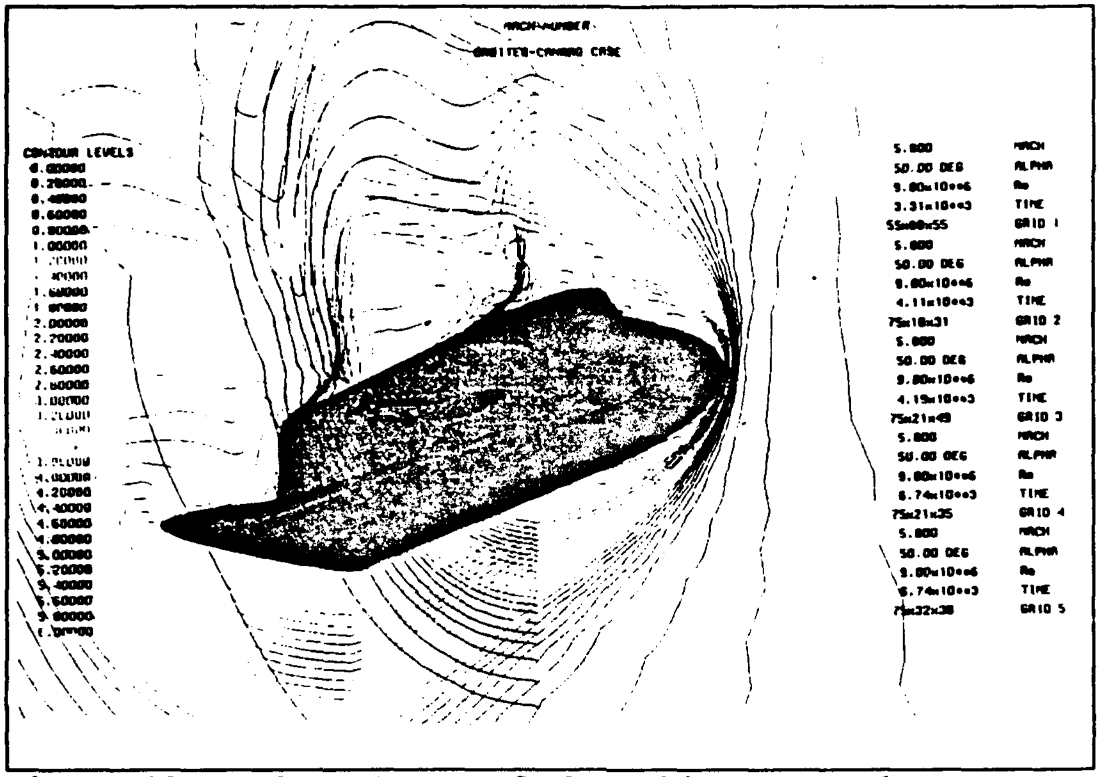

**Figure 11. Mach Contours of the Orbiter-Canard System.**

### 3. Force and Moment Data Extraction

The OVERFLOW code provides the forces and moments for each grid in the form of a formatted output file. The forces are calculated within the code by integrating the calculated pressure and skin friction over the surface of each grid. The resultant moments are calculated about the origin of the coordinate system. In this case, External Tank coordinates were used placing the center of gravity of the Orbiter at $X_o$=1817.7", $Y_o$=0.0", and $Z_o$=686.5".[1] The forces and moments from the baseline and Orbiter-Canard cases were compared to

[1] The *origin of the* External Tank coordinate system is 322.5" upstream and 400" below the External Tank nose.

determine the net force and moment transmitted to the vehicle by the canard. These forces were then compared with earlier predictions and used to determine the elevon-deflection/center-of-gravity relaxation that could be achieved by use of this configuration.

# IV. RESULTS

## A. COMPUTATIONAL GRID

The volume grids for the Glove and NLF Extension required extensive post-processing to make them computationally correct (i.e. positive volume). The input parameters used in HYPGEN produced a correct grid for most of the geometry, but difficult areas such as the tip required local smoothing or averaging. Routines were written to correct these irregularities.

Avoiding very sharp trailing-edges when generating volume grids would have been helpful in creating a smoother grid for the flow solver. The trailing-edge should be slightly blunted to avoid grid lines having to turn nearly 180 degrees over a very short distance.

The resolution of the both the glove and NLF extension tips in a computational sense was also a problem. The surface grids were numbered periodic, or from lower trailing-edge around to upper trailing-edge, in the J-direction and increased in the K-direction from the root to the tip. This numbering convention presented the problem of representing the $K=K_{max}$ plane as a collapsed surface. When the flow solver was employed, the boundary conditions did not allow for such a collapsed "slit" in the grid and communication was slower across that boundary since information was not being effectively transferred across the grid boundary (or slit).

The collar surface grids were split into upper and lower sections when necessary to allow HYPGEN to more easily provide the correct volume grid. Once the two halves were satisfactory, a routine provided by Buning was used to concatenate the grids into one. Avoidance of sharp trailing-edges, again, would have been helpful for the flow solver. The collar surface grids must extend far enough out from the intersection line of the body surface grids to ensure there are enough points for quality interpolation. Once realized, regeneration of the grids to extend the grids was straightforward with the use of the collar grid tools.

The hole boundary and interpolation stencil definition required a number of attempts at providing PEGASUS with the correct hole cutter definition. The final result was an input file that had numerous hole cutters for each grid to ensure there were no orphan points left in the grid. Orphan points are those for which no points are available for interpolation. Care was also taken to cut the holes such that interpolation did not take place in the boundary layer, ensuring a quality viscous computation.

## B. FLOW SOLVER EMPLOYMENT

Once the use of the OVERFLOW code was mastered, generation of the baseline solution was straightforward. The nondimensionalized, volume-scaled time step for the baseline solution was worked up to around 0.1 after about 1200 iterations. Higher than expected smoothing parameters were required to advance this high-Mach number solution as opposed to most of the former work done with OVERFLOW in that this Mach number was the highest to date for which the code had been run. A converged solution was obtained after 1875 iterations and 3.5 hrs on the CRAY Y-MP at NAS. The Mach contours showed that the canard would, in fact fit within the bow shock at this Mach number. The flowfield in the location of the proposed canard was also uniform. Several attempts were made to locate data that could be used to validate the results. There are currently no experimental pressure data for the Orbiter at this flight condition.

Advancement of the Orbiter-Canard solution was, however, more challenging. Lessons learned in the generation of the baseline solution were used for the Orbiter; however, the introduction of the Canard system into the flowfield required that the Orbiter be run at a smaller time step than for the baseline case and with higher smoothing. The NLF extension and the NLF-glove collar grid required the smallest time steps, on the order of .0001, to avoid divergence. This requirement is mostly attributable to the sharp trailing-edges that caused highly-skewed grid cells and small cell volumes; both conditions contribute to limits on stability of the numerical scheme. The solution was advanced to 3000 iterations with all grids going through one local iteration per global iteration. Once the inherent time step limitation of the NLF grids was recognized, these grids were iterated 15 times for every global iteration. The glove and Orbiter-glove collar grids were also iterated 5 times for every Orbiter iteration. This scheme aided in the convergence of the solution. This process was followed until computed residuals had decayed and the force and moment data reached a steady solution. Since the NLF and NLF-glove collar grids were not fully converged due to the low time step, the final solution still had some inaccuracies in shock structure and surface temperature in regions where the NLF and NLF-glove collar grids were communicating to nearby grids. The surface temperatures in the area of the Orbiter wing leading-edge were larger than would be expected from the baseline case. This is attributable to the fact that interpolation between the Orbiter and NLF extension grids was taking place just upstream of the Orbiter wing. The force and moment data for these grids, however, was almost invariant with successive iterations. The solution required about 15 hours of CRAY Y-MP time.

### C. FORCE AND MOMENT RESULTS

The OVERFLOW output file provided the force and moment data due to pressure and friction for the surface of each grid individually. Once the force and moment data no longer significantly varied with successive iterations, the coefficients of lift, drag and side force were extracted and the forces on the glove and NLF extension were calculated. The resulting nose-up moment transmitted to the Orbiter, using the half-chord as the center of pressure, was calculated to be 268,300 ft-lbs. This appears to be a reasonable result considering that the canard was originally sized to produce a moment of 104,600 ft-lbs and was to be deflected down 25 degrees giving it a local angle of attack of 25 degrees. This moment would allow the elevons to be deflected down to 10.62 degrees from the present 26 degrees. If the elevons were deflected down to only 20 degrees as previously suggested, the additional moment could be used to relax the center of gravity requirement forward 10.3" to $X_o$=1807.4".[2] In fact, the glove alone at 50 degrees angle of attack provided 104,000 ft-lbs. This moment is just short of the 104,600 needed to relax the elevon deflection to 20 degrees.

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[2] The current center of gravity limits are from 1817.7" to 1850" in external tank coordinates.

## V. CONCLUSIONS AND RECOMMENDATIONS

The use of a canard by the Space Shuttle Orbiter in both the hypersonic and subsonic flight regimes can enhance its usefulness by expanding its payload carrying capability and improving its static stability. The data indicate that with a small canard in the hypersonic regime, substantial forces can be realized. The glove alone could nearly satisfy the design requirement of relaxing the elevon deflection from 26 to 20 degrees. The NLF extension could be fully stowed during the hypersonic phase of flight and reserved for the low-speed portion of re-entry where it performs well. This configuration would create much less of a heat transfer problem in that the NLF extension would not require extensive thermal protection.

A more extensive analysis should be done throughout the flight envelope to ensure that the canard will perform to expectations. The force data should be incorporated into the software for the Vertical Motion Simulator (VMS) at NASA Ames to obtain pilot handling quality ratings for the chosen flight regimes. The Pre-Landing case solution should be generated to verify the required areas calculated in this report. This case can be compared with experimental results much more readily. A higher Mach number case should be run as well to determine whether the glove will be fully contained within the bow shock when heat transfer is the main concern.

A boundary condition to account for the grid topology employed here should be written as an option in the OVERFLOW code. This addition to the code would quicken convergence rates for such geometries.

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